Towards Realistic Transfer Learning Methods: Theory and Algorithms

A thesis submitted in fulfilment of the requirements
for the degree of

Doctor of Philosophy
in
Computer Science

by

Feng Liu

to

School of Computer Science
Faculty of Engineering and Information Technology
Australian Artificial Intelligence Institute
University of Technology Sydney
NSW - 2007, Australia
2020

Certificate of Original Authorship

I, *Feng Liu*, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the School of Computer Science at the Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

SIGNATURE: Production Note: Signature removed prior to publication.

DATE: 08, Sep., 2020

Abstract

Transfer learning aims to leverage knowledge from domains with abundant labels (i.e., source domains) to help train a classifier or predictor for the domain with insufficient labels (i.e., target domain). The trained classifier or predictor is expected to have better performance (e.g., higher accuracy) than classifiers only trained with data in the target domain.

Although recent research of transfer learning has shown a decent ability to transfer knowledge from a source domain to a target domain, most research require certain assumptions to ensure their efficacy. These assumptions are probably not realistic, which means that existing transfer learning methods still face several unsolved and challenging problems in real world.

This thesis aims to address four orthogonal problems faced by existing transfer learning methods: 1) How to test if feature spaces of two domains are from different distributions; 2) How to transfer knowledge when labels in the source domain cannot be perfectly annotated (i.e., the source domain contains noisy labels); 3) How to transfer knowledge when source and target domains have different dimensions (i.e., heterogeneous scenario); and 4) How to transfer knowledge across multiple source domains and a different-dimension target domain.

To address Problem 1), this thesis presents two new two-sample tests to test

if the feature spaces of source domains and target domain are from different distributions. One is suitable for low-dimension data (Chapter 3) and another for high-dimension data (Chapter 4). If feature spaces of domains are statistically different, we need to use transfer learning methods on these domains. Moreover, the test statistics used in the proposed tests can be used to measure the distributional discrepancy between two domains.

To address Problem 2), this thesis presents a theoretical bound to show that existing transfer learning methods cannot work well when a source domain contain noisy labels. Then, a novel transfer learning approach is proposed to transfer knowledge across a source domain (with noisy labels) and a target domain. Finally, a generalization bound is proved to explain why the proposed method can reliably transfer knowledge across domains in noisy scenario (Chapter 5).

To address Problem 3), the most challenging problem in the field of domain adaptation, Chapter 6 presents a theorem to show when we can reliably transfer knowledge across two different-dimension (i.e., heterogeneous) domains and propose a solution to this problem. Since methods in Chapter 6 assume that the number of samples in two domains must be the same (i.e., two balanced domains), Chapter 7 presents a novel fuzzy-relation based method to transfer knowledge across two imbalanced domains.

To address Problem 4), Chapter 8 presents a novel fuzzy-relation neural network to transfer knowledge from multiple source domains to a target domain, where any of two domains are heterogeneous (i.e., feature spaces of any of two domains have different dimensions).

To conclude, this thesis not only propose a set of effective methods for realistic transfer learning, but also contribute to theory of transfer learning.

Dedication

To my loving wife, parents and families...

ACKNOWLEDGMENTS

It is a memorial and exciting journey at University of Technology Sydney (UTS) for pursuing my Ph.D. degree in the past three and half years. I am sincerely grateful to the people who inspired and helped me in many ways.

I would like to express my foremost and deepest gratitude to my principal supervisor, A./Professor Guangquan Zhang. Without his patience and encouragement, I would not have been able to complete this Ph.D. program. He taught me step by step how to become a qualified researcher from its beginning. He always led me to the right research direction with his expert knowledge of theory and abundant research experience. He placed considerable trust in my research ability and unconditionally support me in pursuing my own research interests. His wisdom and immense knowledge always enlightened me to go further and deeper in my research. Without his critical comments, I would waste my time on trivial research ideas. Discussion with him greatly improves the scientific aspect and quality of my research. He helped me to build my confidence in my research outcomes and to be hopeful when faced with any difficulty, from academic to living.

Meanwhile, I am greatly indebted to my co-advisor, Distinguished Professor

Jie Lu. Her decisiveness and sharp insights continuously motivated me when I got lost or afraid about the future. Her confidence and enthusiasm inspired me to do the right thing even when the road got tough. I felt extremely honored to be guided by such a rigorous researcher as well as an enthusiastic mentor. What she taught me and what I learned from her in the past four years has benefited my Ph.D. study and will be a great treasure throughout my life.

During my Ph.D. period, I am very fortunate to join the Imperfect Information Learning Team as a research intern at RIKEN Center for Advanced Intelligence Project (RIKEN-AIP), working with Prof. Masashi Sugiyama, Dr. Gang Niu and Dr. Bo Han; to join the Gatsby Computational Neuroscience Unit at UCL as a visiting scholar, working with Prof. Arthur Gretton, Dr. Dougal J. Sutherland and Wenkai Xu. I would like to express my thankfulness to Prof. Masashi Sugiyama and Prof. Arthur Gretton that they led me to the machine learning field. Discussion and cooperation with them helped me to deeply understand what the top-tier machine-learning work should be and what characteristics a machine-learning researcher should have. I am impressed and inspired by their persistence, rigour and passion on research.

I would like to express my thankfulness to every member of the Decision Systems & e-Service Intelligence Lab (DeSI) in the Centre for Artificial Intelligence (CAI). It was a wonderful experience to spend four years with these dedicated researchers. I especially thank Dr. Hua Zuo, Dr. Junyun Xuan, Dr. Zheng Yan, Dr. Yi Zhang, Dr. Anjin Liu, Dr. Fujin Zhu, Dr. Feng Gu, Dr. Ning Lu and Zhen Fang who provided insightful comments related to my research problem during my Ph.D. candidature; Dr. Ximeng Wang, Dr. Guanjin Wang, Qian Liu, Dr. Chenlian Hu, Bin Zhang and Bin Wang who have shared their opinions and comments

with me, Dr. Anjin Liu, Dr. Junyun Xuan, Hang Yu and Ruiping Yin who shared my joys and sadness.

I must thank Dr. Gang Niu and Dr. Bo Han for the valuable suggestions for my Ph.D. study. Their persistence, rigour and passion on research impressed and inspired me. I have learned much about how to do an excellent machine-learning research from them. I also express my thankfulness to Dr. Dougal J. Sutherland who patiently guides me how to do an excellent machine-learning research. I am also impressed and inspired by his persistence, rigour and passion on research.

Meanwhile, I genuinely thank Jemima Moore, Sue Felix and Michele Mooney for polishing the language of my publications. They are always patient to all my emails of questioning revised sentences. I thank all my wonderful friends, classmates and colleagues for every enjoyable moment.

Last, I would like to express my heartfelt appreciation and gratitude to my wife, parents, and families for their love and support.

List of Publications

1. **Feng Liu***, Wenkai Xu*, Jie Lu, Guangquan Zhang, Arthur Gretton, Dougal Sutherland. Learning Deep Kernels for Nonparametric Two Sample Test. *Proceedings of the 37th International Conference on Machine Learning* (ICML 2020), online, 13-18 July, 2020. (*Equal Contribution). [ERA: A, CORE: **A***]

2. **Feng Liu**, Guangquan Zhang, Jie Lu, Heterogeneous Domain Adaptation: An Unsupervised Approach, *IEEE Transactions on Neural Networks and Learning Systems* (IEEE-TNNLS), 2020. DOI: 10.1109/TNNLS.2020.2973293. [ERA&CORE: **A***, JCR Q1]

3. **Feng Liu**, Guangquan Zhang, Jie Lu, Multi-source heterogeneous unsupervised domain adaptation via shared-fuzzy-equivalence-relation neural networks, *IEEE Transactions on Fuzzy Systems* (IEEE-TFS), 2020. DOI: 10.1109/TFUZZ.2020.3018191. [ERA&CORE: **A***, JCR Q1]

4. **Feng Liu**, Guangquan Zhang, Jie Lu, Unsupervised Heterogeneous Domain Adaptation via Shared Fuzzy Equivalence Relations, *IEEE Transactions on Fuzzy Systems* (IEEE-TFS), Vol. 26, no. 6, pp. 3555-3568, 2018. [ERA&CORE: **A***, JCR Q1]

5. **Feng Liu**, Jie Lu, Bo Han, Gang Niu, Guangquan Zhang, Masashi Sugiyama. Butterfly: One-step Approach towards Wildly Unsupervised Domain Adaptation, *IEEE Transactions on Pattern Analysis and Machine Intelligence* (IEEE-TPAMI). [ERA&CORE: **A***, JCR Q1] (Revise&Resubmit)

6. **Feng Liu**, Jie Lu, Bo Han, Gang Niu, Guangquan Zhang, Masashi Sugiyama. Butterfly: A Panacea for All Difficulties in Wildly Unsupervised Domain Adaptation, *NeurIPS 2019 Workshop on Learning Transferable Skills*, pp. 1-8, Vancouver, Canada, 8-14 December, 2019. [ERA: A, CORE: **A***]

7. **Feng Liu**, Guangquan Zhang, Jie Lu. A Novel Fuzzy Neural Network for Unsupervised Domain Adaptation in Heterogeneous Scenarios, *Proceedings of the 2019 IEEE International Conference on Fuzzy Systems* (FUZZ-IEEE 2019), pp. 1-6, New Orleans, USA, 2019. [ERA&CORE: A]**[Best Student Paper Award]**

8. Yiyang Zhang*, **Feng Liu***, Zhen Fang, Bo Yuan, Guangquan Zhang, Jie Lu, Clarinet: A One-step Approach Towards Budget-friendly Unsupervised Domain Adaptation, *Proceedings of the 29th International Joint Conference on Artificial Intelligence* (IJCAI 2020), 2020. (*Equal Contribution). [ERA: A, CORE: **A***]

9. **Feng Liu**, Guangquan Zhang, Jie Lu, A Novel Non-parametric Two-Sample Test on Imprecise Observations, *Proceedings of the 2020 IEEE International Conference on Fuzzy Systems* (FUZZ-IEEE 2020), online, 19-24 July, 2020. [ERA&CORE: A]

10. **Feng Liu**, Guangquan Zhang, Jie Lu. Unconstrained fuzzy feature fusion for heterogeneous unsupervised domain adaptation, *Proceedings of the 2018 IEEE International Conference on Fuzzy Systems* (FUZZ-IEEE 2018), pp. 1-8, Rio de Janeiro, Brazil, 8-13 July, 2018. [ERA&CORE: A]

11. **Feng Liu**, Guangquan Zhang, Jie Lu. Heterogeneous unsupervised domain adaptation based on fuzzy feature fusion, *Proceedings of the 2017 IEEE International Conference on Fuzzy Systems* (FUZZ-IEEE 2017), pp. 1-6, Naples, Italy, 9-12 July, 2017. [ERA&CORE: A]

12. **Feng Liu**, Guangquan Zhang, Anjin Liu, Jie Lu, Discrepancy of Diverse Subsets for Distribution Comparison, *IEEE Transactions on Pattern Analysis and Machine Intelligence* (IEEE-TPAMI). [ERA&CORE: **A***, JCR Q1] (under review)

13. **Feng Liu**, Zhen Fang, Guangquan Zhang, Jie Lu, Take A Closer Look at Kernel Nonparametric Two-sample Tests via the Lebesgue-Besicovitch Differentiation Theorem, *IEEE Transactions on Neural Networks and Learning Systems* (IEEE-TNNLS). [ERA&CORE: **A***, JCR Q1] (submitted)

14. **Feng Liu**, Guangquan Zhang, Jie Lu, A Knowledge-Ensemble Model for Heterogeneous Unsupervised Domain Adaptation, *IEEE Transactions on Knowledge and Data Engineering* (IEEE-TKDE). [ERA: A, CORE: **A***, JCR Q1] (submitted)

15. Yiyang Zhang*, **Feng Liu***, Zhen Fang, Bo Yuan, Guangquan Zhang, Jie Lu, Learning from a Complementary-label Source Domain: Theory and Algorithms, *IEEE Transactions on Neural Networks and Learning Systems*

(IEEE-TNNLS). (*Equal Contribution). [ERA&CORE: **A***, JCR Q1] (under review)

16. Hua Zuo, Jie Lu, Guangquan Zhang, **Feng Liu**, Fuzzy Transfer Learning Using an Infinite Gaussian Mixture Model and Active Learning, *IEEE Transactions on Fuzzy Systems* (IEEE-TFS), Vol. 27, no. 2, pp. 291 - 303, 2019. [ERA&CORE: **A***, JCR Q1].

17. Zhen Fang, Jie Lu, **Feng Liu**, Junyu Xuan, Guangquan Zhang, Open Set Domain Adaptation: Theoretical Bound and Algorithm, *IEEE Transactions on Neural Networks and Learning Systems* (IEEE-TNNLS), 2020. DOI: 10.1109/TNNLS.2020.3017213. [ERA&CORE: **A***, JCR Q1]

18. Zhen Fang, Jie Lu, **Feng Liu**, Guangquan Zhang. Unsupervised Domain Adaptation with Sphere Retracting Transformation, *Proceedings of the 2019 IEEE International Joint Conference on Neural Networks* (IJCNN 2019), pp. 1-8, Budapest, Hungary, 14-19 July, 2019. [ERA&CORE: A]

19. Anjin Liu, Jie Lu, **Feng Liu**, Guangquan Zhang, Accumulating regional density dissimilarity for concept drift detection in data streams, *Pattern Recognition* (PR), Vol. 76, pp. 256-272, 2018. [ERA&CORE: **A***, JCR Q1]

20. Yi Zhang, Jie Lu, **Feng Liu**, et. al., Does deep learning help topic extraction? A kernel k-means clustering method with word embedding, *Journal of Informetrics*, Vol. 12, no. 4, pp. 1099-1117, 2018. [ERA&CORE: A, JCR Q1]

21. Li Zhong*, Zhen Fang*, **Feng Liu**, Yuan Bo, Guangquan Zhang, Jie Lu, Open Set Domain Adaptation: Theoretical Bound and Algorithm, *IEEE*

Transactions on Neural Networks and Learning Systems (IEEE-TNNLS). (*Equal Contribution). [ERA&CORE: **A***, JCR Q1] (under review)

22. Qian Zhang, Dianshuang Wu, Jie Lu, **Feng Liu**, Guangquan Zhang, A cross-domain recommender system with consistent information transfer, *Decision Support Systems* (DSS), Vol. 104, pp. 49-63, 2017. [ERA: **A***, JCR Q1]

23. Fan Dong, Jie Lu, Yiliao Song, **Feng Liu**, Guangquan Zhang, A Concept Drift Region-based Data Sample Editing Methodology, *IEEE Transactions on Cybernetics* (IEEE-TCYB). [ERA&CORE: A, JCR Q1] (under review)

Table of Contents

LIST OF FIGURES

FIGURE **Page**

List of Tables

Table **Page**